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Subsidence of Peat in California and Florida

NIKOLA P. PROKOPOVICH, Supervisory Geologist
U.S. Bureau of Reclamation, Mid-Pacific Region, 2800 Cottage Way, Sacramento, CA 95825

ABSTRACT

Subsidence of reclaimed peaty sediments in warm climate is mostly caused by biochemical oxidation and is relatively little known to engineering geologists. Two examples of such subsidence located in areas with major peat deposits, one in the Sacramento-San Joaquin Delta in California and the second one in Florida's Everglades, described in the paper are good illustrations of the potentially enormous economic impacts of such subsidence.

In the 2,835 km^2 Delta, subsidence of original freshwater tidal marsh peat locally exceeded 10–15 m. Initially flat Delta islands became saucer like depressions with surface submerged below the sea level and protected from flooding by some 1,125 km of man-made levees. Levee breaks and inundations of islands already caused multimillion dollar damages and costly repairs and costly pumplift dewatering of flooded islands. With progressing subsidence unavoidable future collapses of levees built frequently with poor materials and on poor foundations in a highly seismic area will cause irreversible flooding of the Delta. Both "soaking" of salt water from the San Francisco Bay and increased evaporation from flooded islands will increase water salinity in the Delta and jeopardize existing giant water conveyance from the Delta to the southern portion of the state. This will endanger the major agroindustry in the arid San Joaquin Valley which depends on importation of surface irrigation water. The annual crop value of the valley is about 7.5 billion dollars.

In the Bell Glade area well studied subsidence caused by agricultural drainage of peat locally exceeds 3 m. Subsidence destroys highly valuable agricultural land and damages buildings, roads, and utilities. Data collected in Bell Glade indicates that such subsidence can be minimized by restriction of drainage, i.e., by properly designed agricultural technique.

Engineering geologists should be aware of possibility of biochemical subsidence in organic soil and suggest 1) its proper monitoring using compaction recorders and common bench marks, and 2) its control and/or arresting by proper design of drainage or restriction of oxidation by blanketing of organic material.

INTRODUCTION

Land subsidence frequently caused by human activities is now a well recognized wide-spread geologic hazard (Bolt et al., 1975). Two factors—an increase in world population and an increase in technology resulted in an alarming spread of subsidence (Prokopovich, 1972). Several modes of subsidence such as subsidence due to underground mining, withdrawal of water, oil and gas, geothermal developments, hydrocompaction and others are well known in engineering geology. Much less known, however, is the land subsidence caused by biochemical oxidation of peat and peaty sediments in warm climate.

The following paper is a brief description of two cases of such subsidence, one in the far western and the second in the southeastern portion of the USA, in California and Florida (Figure 1). In both areas subsidence already causing significant monetary losses will eventually result in direct or indirect multibillion dollar losses.

Peat and peaty deposits in the United States cover an area of about 323,750 km². They are particularly common in the cool humid midwest and coastal northeast. Some 75 percent of the peat-covered land in the USA is concentrated in three states (Figure 1): Michigan, Minnesota, and Wisconsin (Stephens,

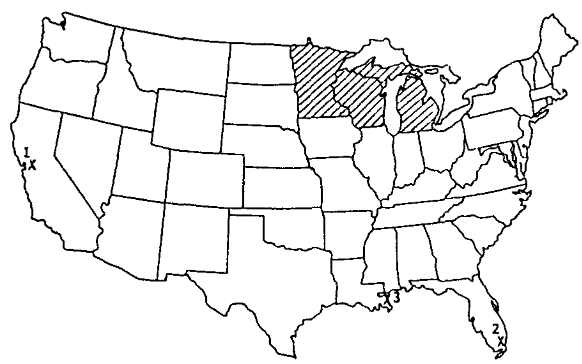


Figure 1. Location map showing the 1) Sacramento–San Joaquin Delta in California, 2) Belle Glade area in Florida, and 3) New Orleans metropolitan area. Hatched area—three states (Minnesota, Wisconsin, and Michigan) having 75 percent of the peat-covered land in the United States.

1969). Peat deposits in these areas and elsewhere in cold climates when drained, are subject to variable amounts of subsidence due to compaction and dehydration (Murashko, 1969; Irwin, 1977; Prus-Chacinski, 1978; and Stephens et al., 1984). In two large, economically important subtropical peat covered areas in the USA—in the Sacramento-San Joaquin Delta in California and in the Florida Everglades—subsidence of peat is caused by biochemical oxidation of organic matter due to man induced changes of anaerobic conditions into aerobic by aeration through drainage. A brief discussion of regional geology, agriculture, subsidence and its consequences in these areas is provided in the following text. Similar subsidence of peat is also known in the Los Angeles and New Orleans areas and elsewhere (Earle, 1975; Fairchild and Wiebe, 1977; Traughber et al., 1979; and Snowden et al., 1977). Proper detection and, at least partial control of subsidence are important but not easy engineering geologic tasks which should be faced prior to any major engineering development in peaty areas.

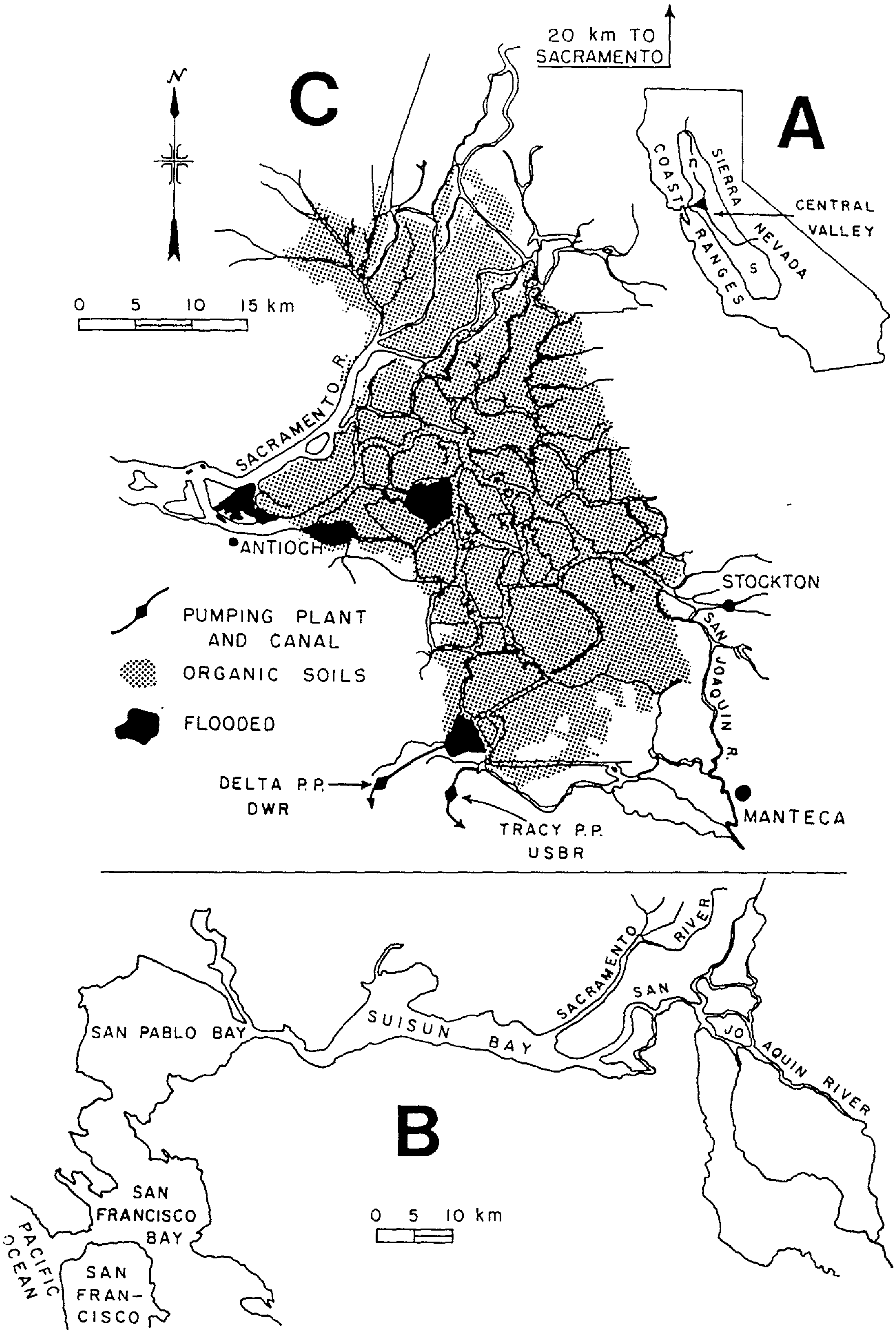
Most of the author's studies of subsidence in peat were sponsored by the U.S. Bureau of Reclamation. The ideas expressed in the paper are, however, those of the author and may not represent official views of the Bureau. The author is deeply indebted to the staff of Belle Glade Agricultural Research and Educational Center of the University of Florida for an informative tour of the area and discussion of local subsidence.

SACRAMENTO-SAN JOAQUIN RIVER DELTA

Location, Hydrology, and Climate

The Sacramento-San Joaquin Delta, or simply the "Delta," is a triangularly shaped area located roughly between the cities of Sacramento on the northeast, Manteca (near Stockton) on the southeast, and Antioch on the west (Figure 2). This approximately 2,835 km² flatland consists of some 100 islands and tracts, including 60 more or less large parcels, surrounded by an approximately 2,250 km-long net of manmade levees and separated by about 1,125 km

Figure 2. Maps of the Sacramento-San Joaquin Delta. A) Location map of the State of California showing the Central Valley located essentially between the Coast Ranges and Sierra Nevada. The northern part of the valley (n), drained by the Sacramento River, is known as the Sacramento Valley and the southern part(s), drained mostly by the San Joaquin River, is known as the San Joaquin Valley. A small black triangle indicates the Sacramento-San Joaquin River Delta. B) Geographic relationships between the Delta, Suisun, San Pablo and San Francisco bays, and the Pacific Ocean. C) Distribution of the main Delta channels and organic Delta soil-peat and peaty sediments (modified from Allsup, 1976).



C
A
B
20 km TO SACRAMENTO
0 5 10 15 km
COAST RANGES
SIERRA NEVADA
CENTRAL VALLEY
SACRAMENTO R.
ANTIOCH
STOCKTON
SAN JOAQUIN R.
MANTECA
PUMPING PLANT AND CANAL
ORGANIC SOILS
FLOODED
DELTA P.P. DWR
TRACY P.P. USBR
SAN PABLO BAY
SUISUN BAY
SACRAMENTO RIVER
SAN JOAQUIN RIVER
SAN FRANCISCO BAY
PACIFIC OCEAN
SAN FRANCISCO
0 5 10 km

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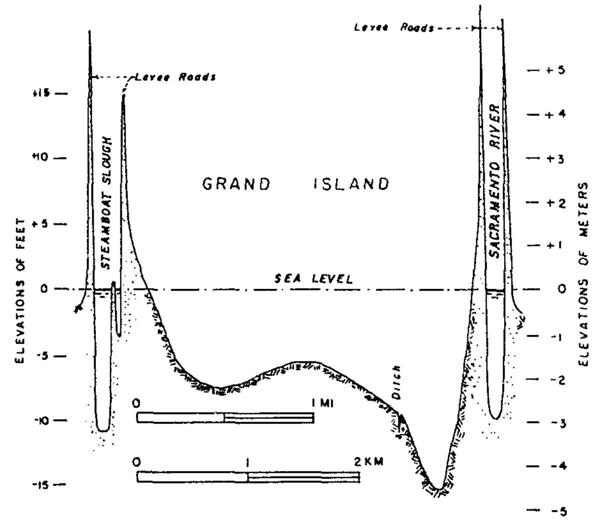


Figure 3. Diagramatic cross-section of Grand Island showing the effect of subsidence of peaty sediments in the interior parts of the island (vertical scale is highly exaggerated). Originally, the interior of the island was at sea level, but has now subsided to below this point.

of channels and sloughs. The actual size of the area, blanketed by peat and highly peaty alluvium, along with associated stream channels, is about 1,312 km^2. The reduced Delta alluvium is usually surrounded by oxidized flood-plain deposits and alluvial terrace deposits. In the downstream direction near Antioch, Delta deposits grade into muck of tidal marshes.

The Delta watershed encompasses about one third (167,313 km^2) of the state and includes two major California rivers—the Sacramento on the north and the San Joaquin on the south (Figure 2). (The Sacramento River provides about 80 percent of the Delta water.) The Mokelumne, Consumnes, and Calaveras rivers provide the east side inflow into the Delta. The total pre-project discharge from all of these rivers amounts to some 36 km^3/yr or to one-half of the combined discharges of all California riverflow (Kahrl, 1979). En route to the Pacific Ocean, these discharges pass through the Delta, the brackish Suisun Bay, San Pablo Bay, and San Francisco Bay (Figure 2). Regardless of proximity to the San Francisco-Oakland, Sacramento, and Stockton metropolitan areas, the Delta has a limited access consisting of a few highways, levee roads and one railroad spur.

The triangular shape of the Delta is misleading. In typical deltas, the river enters into the "head" of the deltaic triangle, the base of which faces an ocean or sea. In the Sacramento-San Joaquin Delta, however, major rivers enter at two opposite (northern and southern) "heads," while the third, western head acts as an outlet to a series of ocean-connected bays. Moreover, typical deltas grow seaward, while marsh deposits of the California Delta, following the Holocene rise of sea levels, have grown landward, with the oldest and thickest peat deposits located in western and central portions. Geologically, the Sacramento-San Joaquin Delta is a progressively filled Holocene estuary formed by the flooding of a pre-Holocene valley (Shlemon, 1971; Shlemon and Begg, 1975). The deeply rooted name "Delta" is, however, retained in this paper.

The original landscape of the Delta, a tidal freshwater marsh, was flat with elevations close to sea level. The only exceptions were broad, low, sandy-silty natural levees deposited during floods. Sand from some of the levees, river channels and terraces was locally reworked into 3 to 6 m high eolial ridges and dunes, many of which became destroyed by ploughing and leveling. The present Delta landscape is a peculiar assemblage of islands with interior depressions caused by the subsidence of peat (Figure 3) and spared from flooding by manmade levees.

Flow patterns in the Delta were originally controlled by tidal intrusions and river inflows, governed by seasonal changes. A third critical factor, exportation of Delta water southward into the San Joaquin Valley and Southern California was added with the completion of the Federal Central Valley Project (CVP) and the State Water Project (SWP) which are shown in Figure 4 (Anonymous, 1974, 1981a). During preproject time, waterflow governed by the Sacramento River occurred in a generally westward (downstream) direction. Under presently existing conditions, particularly during dry years, a modified southward flow (toward the points of pump lift) has developed.

The area has a Mediterranean-type climate, influenced by moist marine air. About 82 percent of the precipitation occurs in November–March. The average rainfall amounts to about 40.6 cm per year. Winter freezing is uncommon. The average summer temperature is 21°C, while the average winter temperature is about 10°C. Heavy, dense winter fog is common. Regardless of proximity to the ocean and river, local agriculture requires artificial irrigation.

Present water quality in the Delta depends on 1) river inflow, 2) tidal action, 3) evaporation within the Delta, 4) irrigational and industrial water consumption in the Delta, 5) agricultural, municipal and industrial pollution and 6) water export by CVP

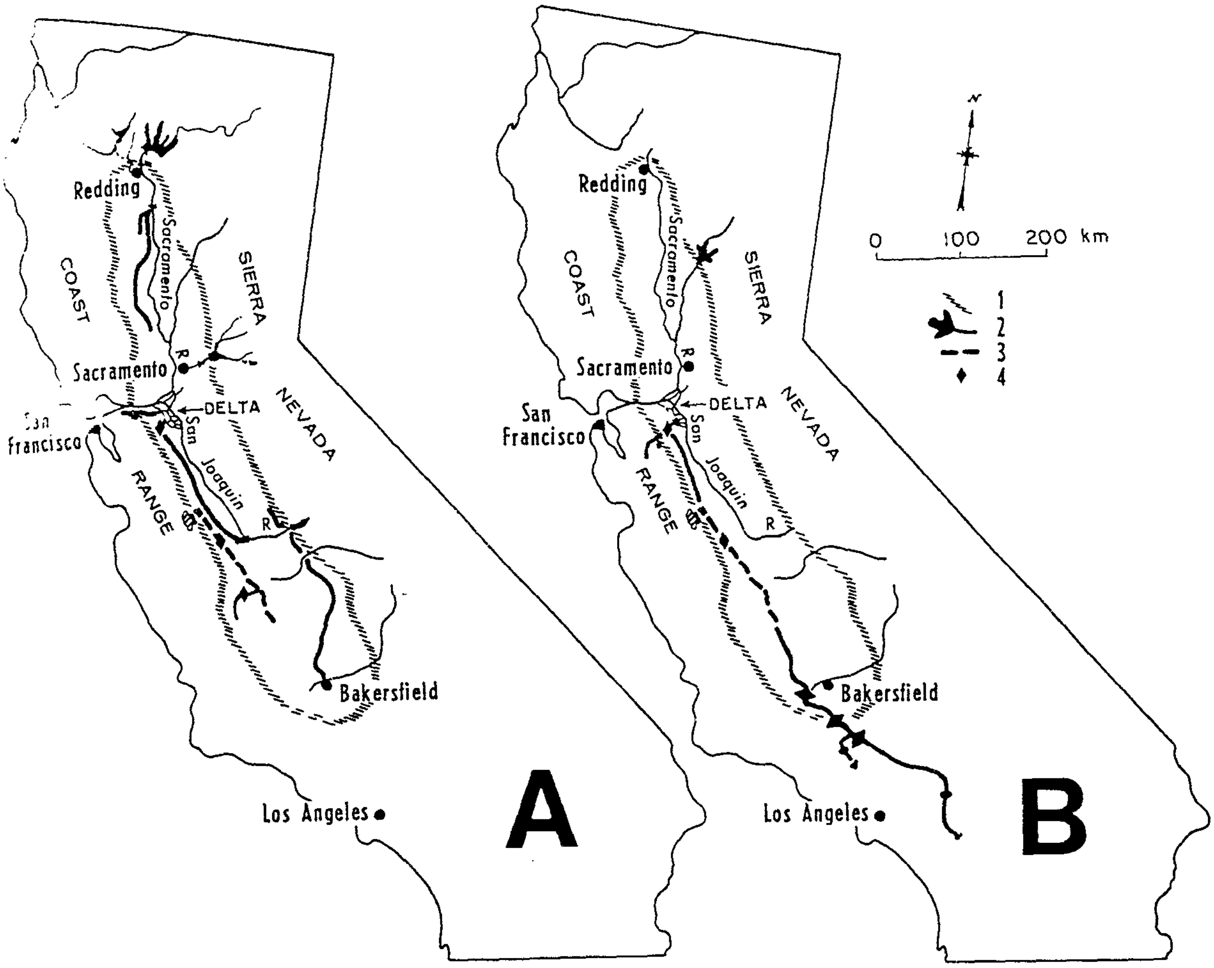


Figure 4. Generalized maps of California showing main features of the A) Federal Central Valley Project (CVP), and B) State Water Project (SWP). 1. Outline of the Central Valley, 2. Main CVP and SWP dams and canals, 3. Joint Federal-State features, and 4. Main pumping plants.

and SWP. Prior to the construction of CVP and SWP, during summer–fall months of low river flow, salty bay water intruded into the Delta by tidal action. For example, on some occasions the chloride content of the Sacramento River at the City of Sacramento reached 1,000 ppm (Skinner, 1972). Since the 1860's, the construction of a downstream salinity control barrier has, therefore, been considered at several points in the Delta (Anonymous, 1978). The idea was abandoned in the 1930's with the decision to provide salinity control by a system of upstream dams and reservoirs. Salt water intrusions resulted in crop damages and salinization of Delta soils.

Present environmental conditions in the Delta are entirely artificial. They have very little in common with the extinct, original, tidal marshland inhabited by elk, bear, and other wild animals. Only little native vegetation is preserved on a few small, unleveed channel islands. Two major fish species in the Delta, striped bass and catfish, were artificially introduced and the most common mollusk is the exotic *Corbicula fluminea,* an Asiatic clam.

History and Economy

Prior to its "discovery" in 1772 by Captain Pedro Fages, the Delta was populated for at least 4,000 years by several Indian groups which usually inhabited sand dunes and natural levees. In some burial grounds, artifacts and bones have been subjected to carbonate cementation. Hence, Indian settlement

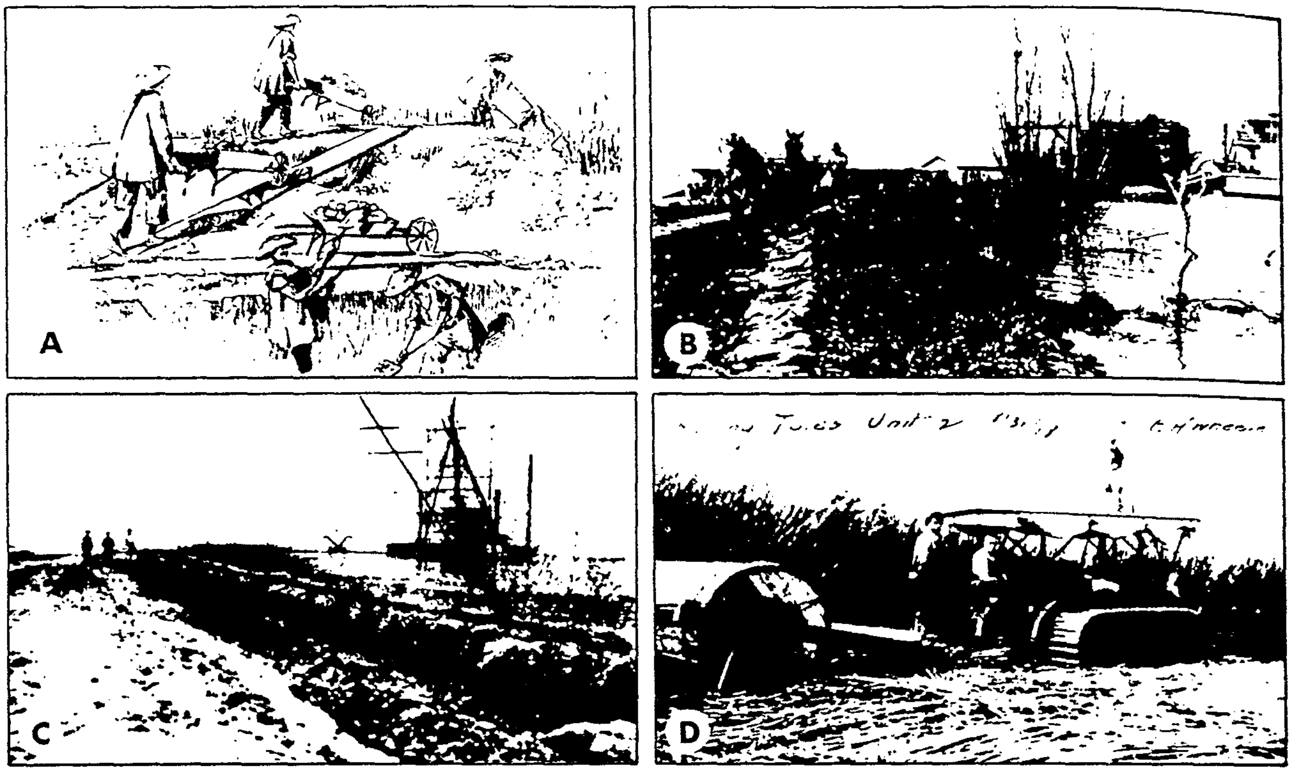


Figure 5. Reclamation of the Delta. A) Typical XIX century construction of levees in the Delta area using Chinese labor and locally available construction materials (Peatfield, 1894); B) and C), more advanced techniques of levee construction using horse-driven equipment (B) and dredging (C) [Dutra Collection, Rio Vista, California]; D) Removal of native vegetation on a newly reclaimed Delta island in August 1918 [Gus Olsen Collection, University of California, Davis]. All photographs are courtesy of the Dutra Museum of Dredging, Rio Vista, California, and are from the originals in the Department of Special Collections, University of California Library, Davis, CA.

preceded the epoch of cementation. The first map of the area appeared in 1850.

From 1772 to 1850, the area was visited mostly by trappers, but a few farmers settled here at the beginning of the Gold Rush Era. Since 1852, these farmers began constructing the first hand-built levees in order to protect themselves from flooding. In 1860–1866, the first reclamation districts were established in the Delta. After completion of the Central Pacific Railroad, scores of Chinese laborers were transferred to the Delta and were used in the construction of levees (Figure 5A). More advanced methods—using horses, mules (Figure 5B) and, later, tractors—were introduced thereafter. After construction of levees, the native vegetation was removed either with equipment (Figure 5D) or sometimes by burning, and the terrain was then used for farming.

The introduction of hydraulic gold mining in the Sierra Nevada filled the Delta with some 600 million m^3 of tailings, clogging river channels and causing frequent and severe floods. More advanced levee construction using clamshells to dredge materials from the bottom of clogged channels (Figure 5C) was introduced, therefore, in about 1910 (Thompson and Dutra, 1983). During these modifications, originally meandering sloughs and channels were "improved" and straightened. Some old channels were bridged by levees and some new straight waterways were excavated across original islands (Figure 6A, B, C). Finally, in the 1930's, reclamation of the Delta was essentially completed, and Delta islands appeared in more or less their present configuration.

Delta precipitation and its seasonal distribution are insufficient for agricultural development, which requires artificial irrigation. Initially, such irrigation was accomplished by the opening of levee gates during periods of high water, with excess water being released through the same gates at low tide. As subsidence progressed, however, gravity release of water became impossible and farmers were forced to pump excess water from islands (Figure 6D), while irri-

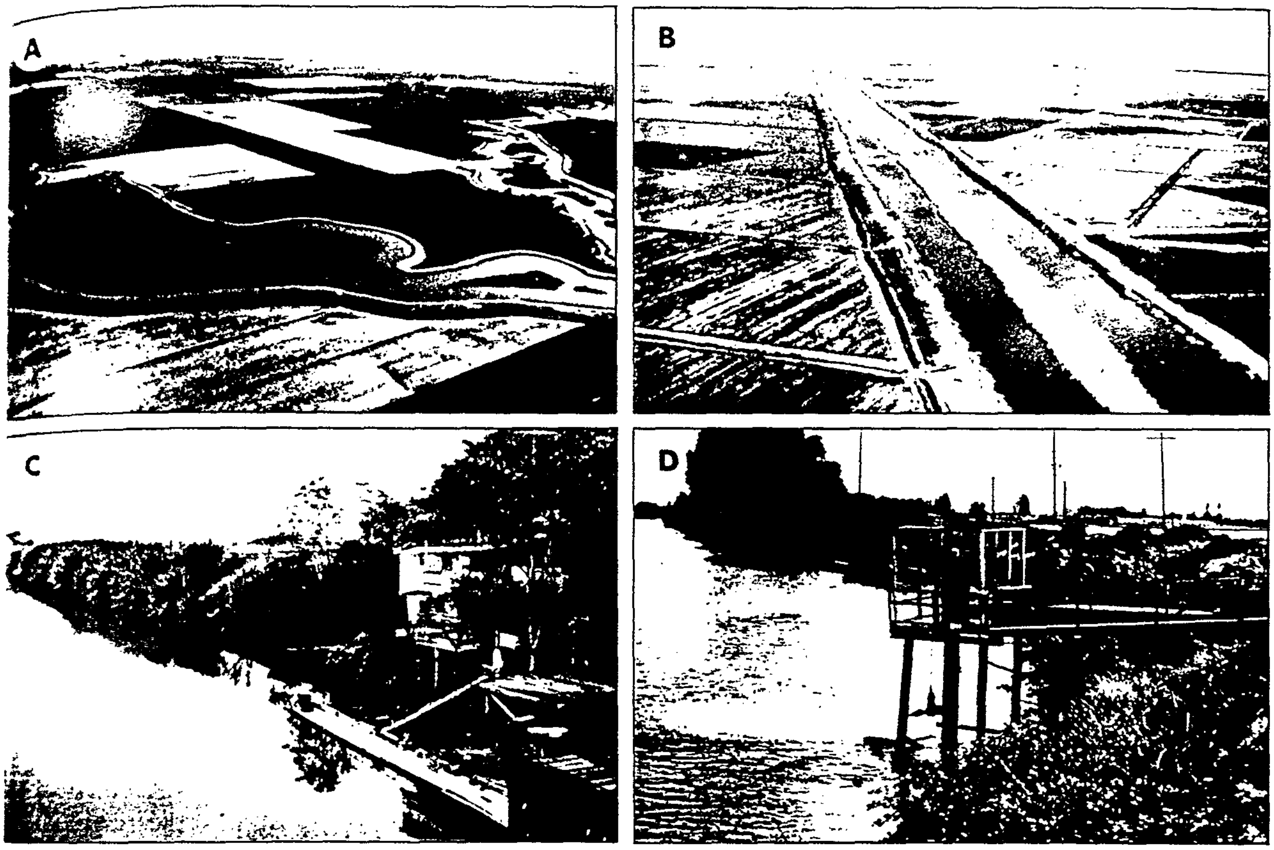


Figure 6. Sacramento–San Joaquin Delta. A) Meandering Delta slough. White slough between Empire and Terminous tracts (June, 19̄78). B) Victoria and North canals between Victoria and Union islands (June, 1978). C) Closeup view of a manmade straight canal in th... ...ern Delta (1964). D) Pumping of drainage water into Burns cutoff from Lower Roberts Island, west of Stockton (Jacob Roa... ...rns cutoff, September, 1981).

gational water deliveries were usually accomplished by overbank siphoning. At the present time, the ground-water table of Delta islands during the irrigating season is raised from a depth of about 1 to 1.2 m to a depth of only 0.1 to 0.3 m. Irrigation is accompanied by drainage, with the main drains being 2 to 3 m deep.

...77 percent of Delta land is used now for agriculture. Local organic soils were considered to be excellent for vegetables and in the past the area was the most productive agricultural district in the state. The shift from vegetable to field crops, increasing soil salinity and costly drainage and weed control, however, have diminished the agricultural value of the present Delta land. Estimated current an... ...lue of Delta crops is still about $375 million (...march, 1981).

The importance of the Delta as a recreational area for boating, waterskiing, fishing and camping is increasing due to its proximity to major urbanized centers (Anonymous, 1981b, 1982). The area is also an important fish spawning route. It is crossed by two deep water navigation channels with annual commercial shipping amounting to some 8 million tons of cargo (Anonymous, 1982).

Delta islands have several important gas fields (Anonymous, 1973b). They are crossed by several high tension powerlines, an aqueduct and other pipelines, and the Atchison-Topeka and Santa Fe Railroad spur.

Most critically, however, the Delta is a key link in the large water conveyance systems of the CVP and SWP (Anonymous, 1974, 1981a; Prokopovich, 1984).

Regional Geology

The Delta occupies a structural trough connecting the Central Valley with the Pacific Ocean via San Francisco Bay. The present Delta is of Holocene age and is the latest of several estuarine systems which existed in the area and were controlled by Pleistocene fluctuations of ocean levels related to glaciations. In the Delta area, such changes caused an alteration of several cycles of erosion and deposition. Most of the sediments deposited during early depositional cycles were, however, removed by subsequent erosion (Shlemon and Begg, 1975).

The present Delta represents the youngest postglacial cycle of this deposition. Its transgression flooded a broad pre-Holocene valley, modifying it into a freshwater tidal marshland. Continuous deposition of peaty sediments in the marshland progressed eastwardly with the advancing transgression and the thickest peat (10 to over 16 m) accumulated, therefore, in the west-central portion of the Delta, in Pleistocene channels of the Sacramento and San Joaquin rivers. Thinner and younger peat, less than 5 m thick, frequently contaminated by inorganic mud, accumulated at the eastern and southern margins of the Delta as shown in Figure 7 (Allsup, 1976; Newmarch, 1981; and Shlemon and Begg, 1975). The deposition of peat on Delta islands was accompanied by deposition of sand, silt and clay in Delta channels and sloughs. Due to bank erosion and migration of channels, layers of reworked peat are frequently present in channel deposits, while some layers of clay, silt and sand, deposited during floods or in ancient stream channels, are present on many Delta islands.

Several major fault zones (Jennings, 1975; Hart, 1976), including the well-known San Andreas, Calaveras, and Hayward faults, are located in close proximity to the Delta (Figure 8), which is itself crossed by the probably inactive Tracy-Stockton and Midland fault zones (Kearney, 1980; Jennings, 1975). A provocative study by Shlemon and Begg (1975) has suggested the existence of Holocene tectonic movements in the Delta along the previously unknown Rio Vista fault. There is also some fragmental indication of the existence of Holocene tectonic subsidence in the Delta area.

A major local earthquake will result in liquefaction and in collapses of Delta levees of major if not catastrophic proportions. It is true that no direct failures of the relatively low 1906 levees were reported in the Delta during the famous San Francisco earthquake. The quake, however, caused foundation settling of several Delta bridges and may have weakened levees resulting in the 1907 flooding of 53 of the major Delta islands. The most recent but distant Coalinga earthquake of 1983 resulted in cracking and slumping of natural ground and levee embankments in numerous places in the central Delta. Similar cracking was also noted during two smaller but less distant earthquakes (Finch, 1985).

Subsidence and Flooding of Delta Islands

Original fresh-water tidal tule-reed Delta marshes located at sea level elevation were constantly inundated by ocean tides and river floods. The shallow ground water table under such conditions frequently merged with floodwater creating anaerobic media. Agricultural reclamation of leveed Delta islands and associated cultivation plowing and drainage changed the near surface anaerobic conditions into aerobic and arrested deposition of new layers of peat. In the warm California climate these changes lead to an intense microbiologic oxidation—"burning" of organic matter and to land subsidence of Delta islands. The reclamation was accompanied by intentional burning of fields conducted in order to kill weeds and to remove old stubble and by wind erosion of open, dry plowed fields during severe "black" dust storms in the Delta.

Suprisingly, regardless of the great economic value of the area no systematic studies of local subsidence were conducted and only a few papers (Weir, 1950) describing the phenomenon were published until recent years. Numerous reports discussing land subsidence and flood protection in the Delta were, however, issued in the 1970's and 1980's usually in connection with operation of SWP and flood protection of the Delta by the State of California Department of Water Resources (DWR) (Anonymous, 1973a, 1975, 1981b, c; Allsup, 1976; Carter, 1980; Burke, 1980; Newmarch, 1980, 1981; and Whitlow et al., 1979) the Army Corps of Engineers (Anonymous, 1982) the U.S. Geological Survey (Atwater, 1982; Atwater et al., 1977; and Atwater and Belknap, 1980), and by several individuals (Shlemon, 1971; Shlemon and Begg, 1975; and others). Some of the information summarized in these papers is of original character, but some is based on reevaluation of studies conducted elsewhere.

Initially, in 1920, it was believed that Delta subsidence was caused by a compaction of fields by heavy equipment and that the process would decrease in the future with completion of near-surface compaction. This optimistic prediction did not materialize (Weir, 1950). The following nine potential causes of subsidence are listed in recent publications (Burke, 1980; Newmarch, 1980, 1981; and others): 1) oxidation, 2) shrinkage, 3) wind erosion, 4) tectonic movements, 5) compaction, 6) anaerobic de-

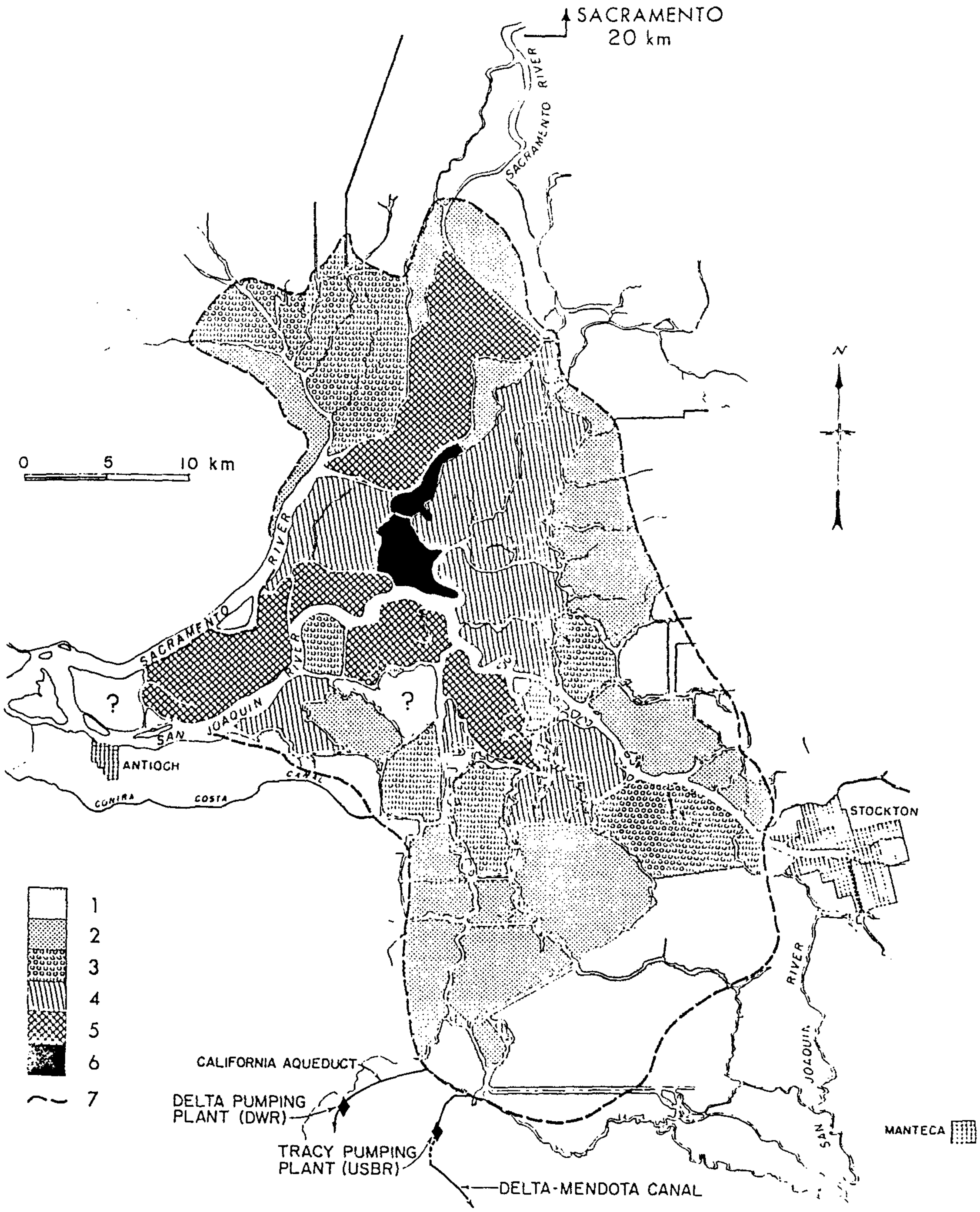


Figure 7. Map showing maximum thickness of peat in individual islands, modified after Newmarch (1981), and others. Maximum thickness of peat: 1) less than 3 m; 2) 3 to 4.9 m; 3) 5 to 7.5 m; 4) 8 to 9.9 m; 5) 10 to 13 m; 6) over 16 m; 7) generalized limit of peat soils.

composition, 7) consolidation of deeply seated beds by withdrawal of gas and water, 8) burning, and 9) export by people. (Actually, results of burning, wind erosion and export by people should not be considered as "subsidence.") The most important of these causes is the man-induced biochemical oxidation of organic matter.

Several Delta islands (Brannan, Twitchell, Tyler

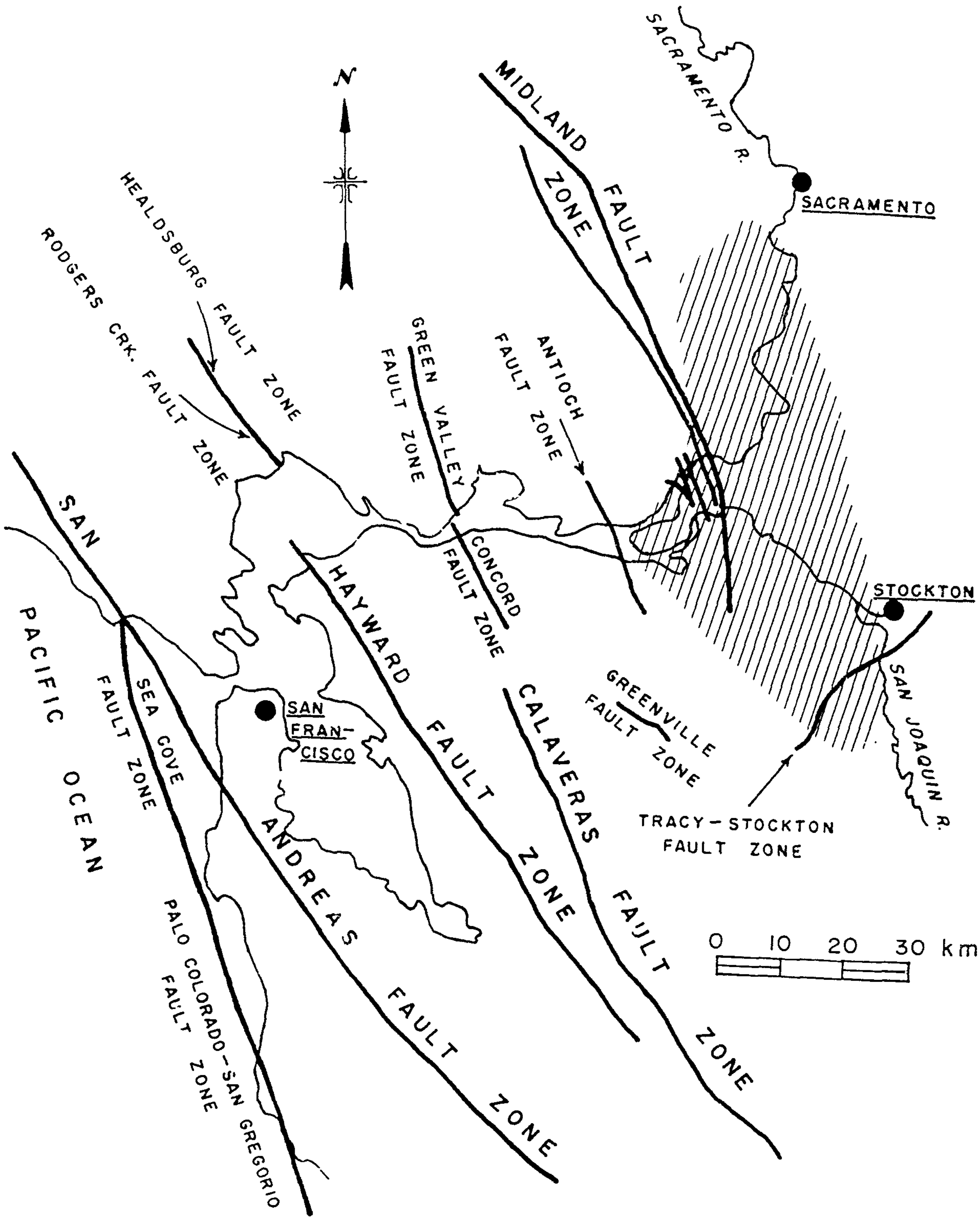


Figure 8. Map showing Quaternary fault zones in the vicinity of the Delta. Modified after Jennings (1975), and others. Crosshatched area indicates area of deltaic peaty sediment.

and others) with producing gas fields (Anonymous, 1973b) show large amounts of subsidence. A comparable amount of subsidence, however, has been registered on neighboring islands having no gas fields. Hence, the impact of gas production on subsidence is uncertain or limited.

Subsidence due to overdraft of ground water is known to occur in mineral soils in the Stockton area (Nicklen et al., 1967). Little pumping of deep, usually saline, aquifer systems takes place, however, on typical Delta islands (Kabakov, 1956; McClure et al., 1956; and Velsh et al., 1955). Hence, no significant subsidence could be caused by development of deep aquifer systems in the Delta.

The great thickness of Holocene peat deposited at sea level is generally explained by the global Holocene rise of ocean levels due to melting of ice caps. In several areas, for example near Clifton Court, some mineral alluvial non-Delta terrain is located below sea level, suggesting possible minor Holocene tectonic subsidence.

Study of subsidence in the Delta is hampered by inadequate historical leveling data. Most of the bench marks in the area are located on roads which are situated on manmade levees. Relatively few points are surveyed on the interior portions of Delta islands, which are subjected to maximum subsidence.

Total amounts of past subsidence range in the Delta from 6.4 m (Tyler Island) to traces. Maximum subsidence ranging from 3.7 to 6.4 m took place on 10 centrally located islands. Some 11 other islands had 3 m of subsidence (Newmarch, 1981) while relatively little subsidence occurs in the eastern and southern portions of the Delta underlain predominantly by inorganic soil with a limited amount of organic matter (Figure 9).

The current, highest subsidence rates in the Delta, according to the cited sources, range from 2.8 to 7.7 cm/yr (Tyler Island, south part). In general, maximum subsidence rates and maximum subsidence occur on islands with the thickest peat deposits (Figure 7) i.e., located along the broad, pre-Holocene, "T" or "Y"-shaped channels in the western and central portions of the Delta.

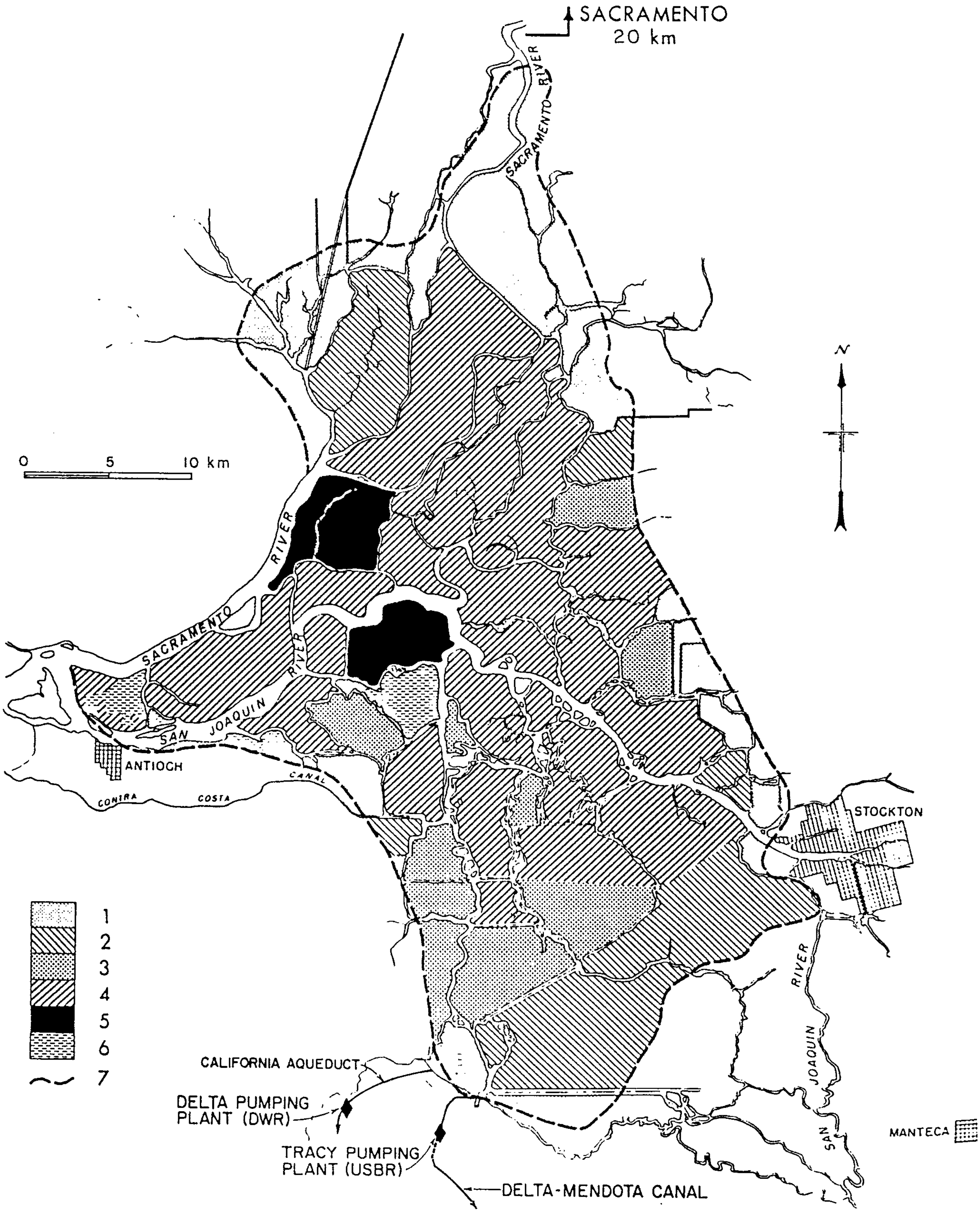
Generally, subsidence reaches its maximum in central parts of islands where original peat deposits approach their maximal thickness. Such subsided islands develop typical "bowl"-shaped configurations (Figure 3).

The impact of subsidence is clearly visible on numerous structures located in the Delta. Many buildings, piers, towers and other structures originally built on piles have become elevated and their foundations have become air-exposed. In many places it is visually obvious that water levels in streams and sloughs are situated *above* the surrounding land, protected only by levees (Figure 10).

All available data (Newmarch, 1980, 1981; Burke, 1980) indicate that even a major, and probably unrealistic, modification of the existing agricultural practices, may reduce subsidence rates by some 30 percent but not completely arrest it. (Interesting studies of the impact of alfalfa on microbiota and restriction of subsidence were made recently by Levanon and others (1982) and by Levin and Shoham (1984).) It can be stated, therefore, that future continuation of subsidence in the Delta is unavoidable.

Unfortunately, consolidation of Delta sediments is not restricted to cultivated fields, but also occurs under levees. Original sloughs and channels flanked by natural levees had irregular sinusoidal shorelines which were "improved" and straightened during construction of manmade levees (Figure 6A, B, C). The approximate distribution of old Delta channels was recently mapped by Atwater (1982). Consequently, many of the present levees were poorly designed, poorly constructed and placed on poor foundations, with layers of peat and highly organic sediments. Similar materials, together with dredged channel sand and silt, were also used in the construction of embankments of old levees. Such foundation and fill materials have a low shear strength and high compressibility and, at the present time are highly polluted. The weight of the original levee fill plus the weight of newly added fill during rehabilitation of levees resulted in notable compaction of foundations and embankments, and in the settling of levees (Anonymous, 1982). Due to compaction, crests of many levees became uneven and "bumpy." Such "subsidence" of levees is caused by mechanical loading and is genetically different from subsidence of Delta islands, caused by biochemical oxidation (Prokopovich, 1985). The rehabilitation of levees is additionally complicated by the absence of locally available, proper borrow materials, an 80 to 150 km haul of such materials is considered by the Army Corps of Engineers (Anonymous, 1982). Several other factors such as different ownership, locally poor maintenance, erosion by wind and boat waves, destruction by animals, etc. are equally important. Particularly critical, due to high seismicity of the area, is potential liquefaction of levee foundations during a major earthquake.

The most spectacular and known result of sub-


SACRAMENTO
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SAN JOAQUIN RIVER
ANTIOCH
CONTRA COSTA CANAL
STOCKTON
1
2
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6
7
CALIFORNIA AQUEDUCT
DELTA PUMPING PLANT (DWR)
TRACY PUMPING PLANT (USBR)
DELTA-MENDOTA CANAL
SAN JOAQUIN RIVER
MANTECA

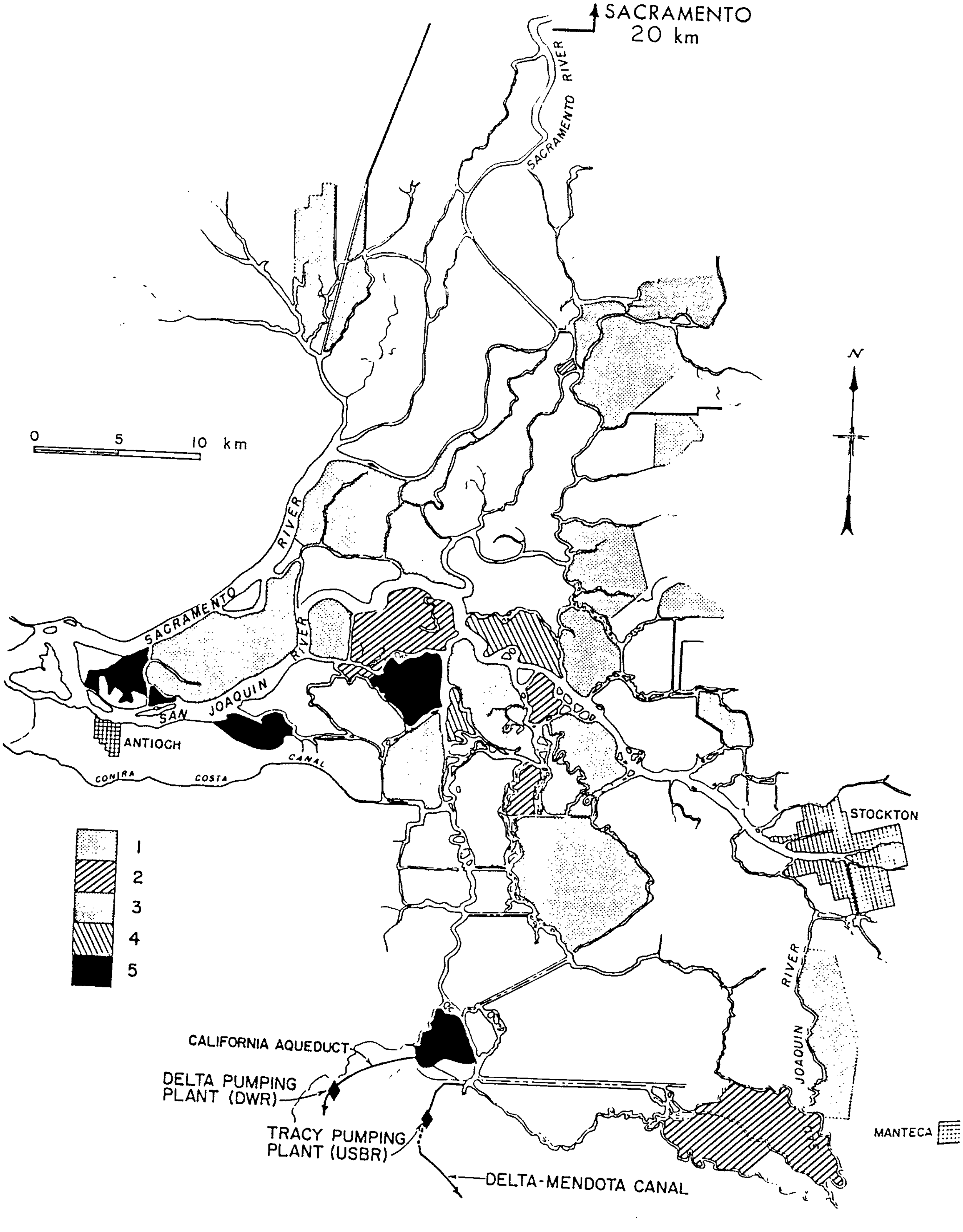
D-030387

Figure 10. Selected examples of subsidence of peaty soil in the Delta: A) Exposure of the Foundation of a transmission tower at the and E Middle River Substation on upper Jones Tract. Position of the original land surface is indicated by an arrow (September, 1981); B) Exposure of foundations of the East Bay Aqueduct pipeline piers on upper Jones Tract, near Middle River. Position of the original land surface indicated by an arrow (September, 1981); C) Byron Tract at Old River looking from State Highway 4. Water level in the river is well above the island surface (March, 1981); D) Old barn built on piles at the soil level became elevated due to oxidation of peat (Holland Tract). Photograph is courtesy of the State of California Department of Water Resources. Amount of subsidence shown on photographs A, B, and D represents subsidence occurring within the depth of the foundation which is only a fraction of the total subsidence.

sidence of the Delta is frequent flooding of its islands. It has been estimated (Anonymous, 1982) that prior to 1910, "natural" winter-spring floods annually inundated some 70 percent of the Delta. After these natural floods, in the 19th century, numerous intentional floodings of newly reclaimed Delta islands were practiced for agricultural irrigation. Such flooding was accomplished by the opening of tidal gates at periods of high tide. Floodwater was then released by gravity flow during low tide intervals. With advances of subsidence, such releases of floodwater became impossible.

A new period of flooding, this time unintentional, started somewhere between 1920 and 1930. No exact records are available on the number or date of the early floods. Some 100 levee failures, however, were estimated to have occurred since the early 1900's (Anonymous, 1982). Most of the flooded islands were rapidly reclaimed, but four—Big Break, Frank's Tract, Lower Sherman and Donlan is-

Figure 9. Map showing maximum amount of subsidence on individual islands (based on an interpretation of USGS topographic quadrangle maps). Maximum subsidence: 1) less 1.5 m; 2) 1.6 to 3 m; 3) 3.1 to 4.5 m; 4) 4.6 to 6 m; 5) over 6 m; 6) not reclaimed, permanently flooded islands (excluding purposely flooded Clifton Court Forebay of the SWP), and 7) generalized "0" elevation contour.


SACRAMENTO
20 km
SACRAMENTO RIVER
0 5 10 km
SACRAMENTO RIVER
SAN JOAQUIN RIVER
ANTIOCH
CONTRA COSTA CANAL
STOCKTON
1
2
3
4
5
CALIFORNIA AQUEDUCT
DELTA PUMPING PLANT (DWR)
TRACY PUMPING PLANT (USBR)
DELTA-MENDOTA CANAL
SAN JOAQUIN RIVER
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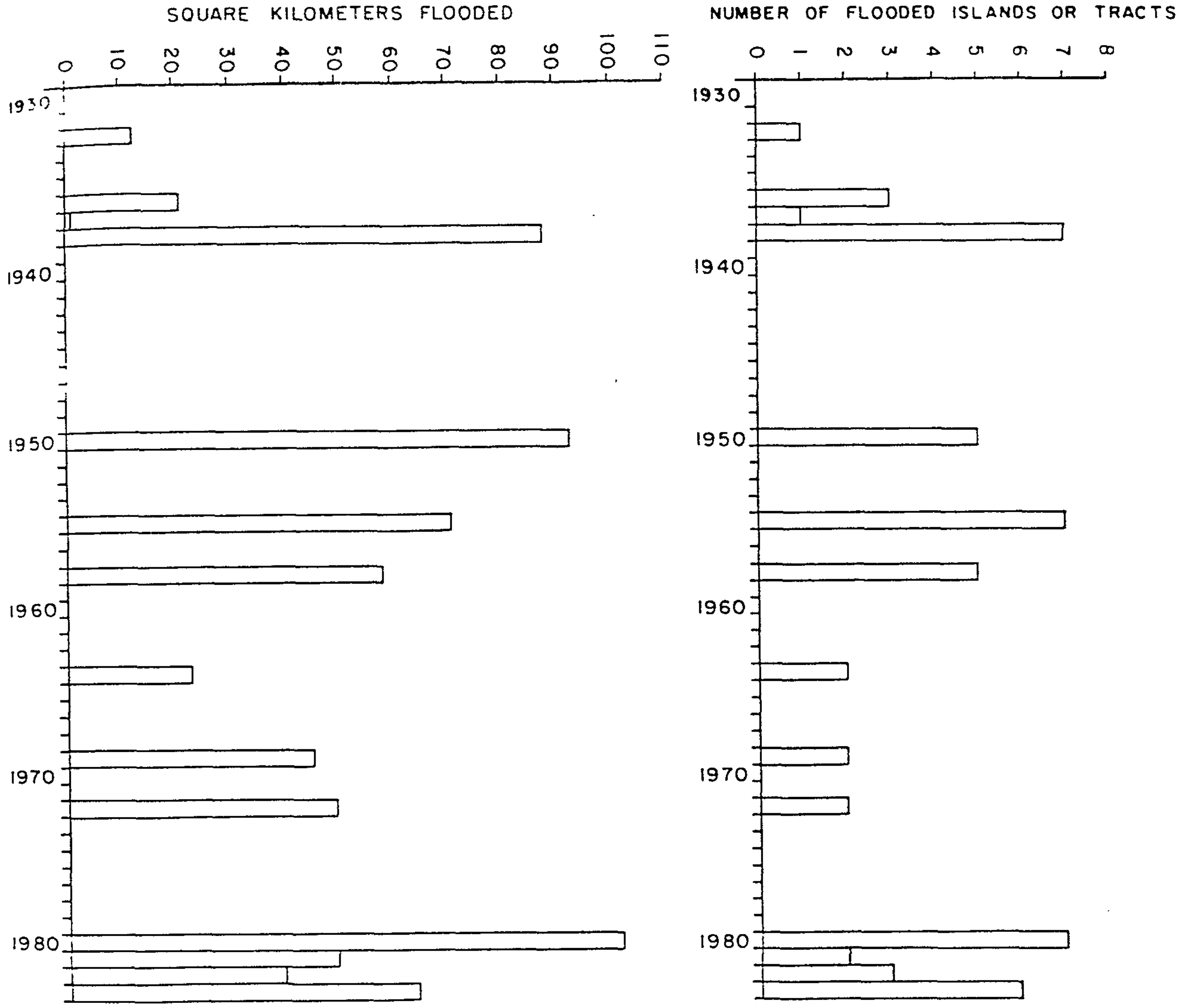

Figure 12. Graphs showing size of flooded areas and number of flooded islands from 1930 to 1983. Assembled from various sources.

lands—were left permanently flooded. A fifth island, Clifton Court, was purposely flooded during construction of the State Water Project (Figures 2 and 11).

A summary of recent floods in the Delta based on several publications (Anonymous, 1982) and newspaper releases is shown in a map in Figure 11 and a diagram in Figure 12. Selected photographs of flooded islands and their rehabilitation are shown in Figures 13, 14 and 15.

Early unintentional flooding was mainly a result of the overtopping of levees by floodwater during either particularly high tides or uncontrolled winter-spring floods. As the subsidence of islands during this stage was relatively minor, the pump-lift of floodwater and reclamation of islands was relatively

Figure 11. Map showing 1930–1983 frequency of inundation of Delta islands. Modified from several sources 1) inundated one time; 2) inundated twice; 3) inundated three times; 4) inundated four times; 5) not reclaimed, permanently flooded (including purposely flooded Clifton Court Forebay of the SWP).

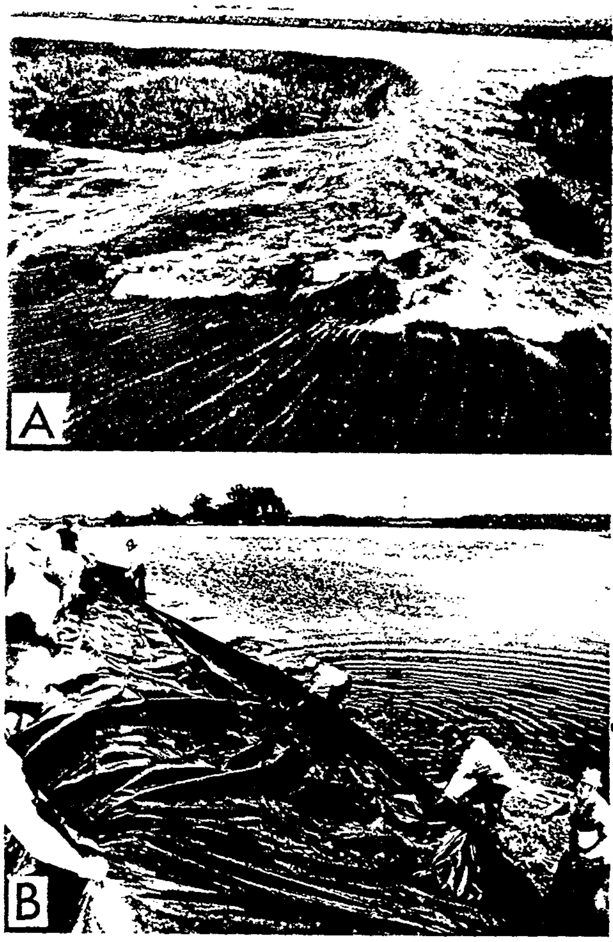

Figure 13. June 1972 flooding of Andrus-Brannan Islands. A) Floodwater rushes through a small island near the levee break. B) Sheets of plastic are installed over a newly constructed barrier to prevent its destruction by floodwater. (Photographs by the Sacramento Bee.)

inexpensive. This phase of flooding was terminated in the 1940's with flood control being provided by the construction of CVP (and thereafter SWP) dams on Central Valley rivers.

During the following "lull" of flooding, continuous subsidence lowered the interior portions of islands and created progressively increasing heads between ground-water levels in subsided islands and the surrounding channels. Vertical sinks, cracks, and boils started therefore to develop on the landside slope of some levees. The process led to several inundations of islands, due to levee failures rather than overtopping. For example (Anonymous, 1982), 12 of 18 failures occurring since 1950 were caused by foundation failure and 6 by overtopping.

Particularly spectacular and alarming was the June 1972 failure of Brannan-Andrus Islands (Cook and Coleman, 1973) which occurred during a relatively dry, low outflow period (Figures 13 and 14). This flooding resulted in a major "soaking" of salty bay water into the Delta (Figure 16).

Large releases from CVP and SWP dams (and correspondingly large potential income losses) are needed to neutralize salt intrusions related to such failures. Losses caused by flooding include cost of levee repair, cost of pump-lift drainage of floodwater, losses of buildings, crops, utilities, livestock, et cetera. Recent floods of lower and upper Jones Tracts jeopardized water deliveries to the East Bay Area via the Mokelumne Aqueduct, and disrupted operation of the Santa Fe Railroad (Anonymous, 1982). (As the Delta is essentially rural and sparsely populated, human losses until now have been absent.)

No complete data on cost of levee repairs and dewaterings as well as on losses due to flooding of Delta islands are readily available. The sum is, however, very large. For example, from 1969 to 1983, flood losses on 11 of the 28 islands that flooded during this time period amounted to about $177 million. According to newspaper articles in the "Sacramento Bee" (December 29, 1983), state and federal expenditures on levee repairs in 1981–83 amounted to some $60 million. According to Anonymous (1982, p. 46), crop losses during August 1982 flooding of McDonald Island amounted to $5.3 million, while levee repairs and dewatering costs amounted to another $6.3 million. Fall 1980 flooding of the Lower and Upper Jones Tracts resulted in $50 million in expenditures for levee repair (Anonymous, 1982; p. 45 and p. 47). The Andrus-Brannan Island flooding of 1972 resulted in an evacuation of 2,000 residents and total damages of some $97 million (Anonymous, 1982; p. 47 and p. 49).

With continuing subsidence, the existing levees will unavoidably begin to weaken, and higher, stronger levees will be required. Several methods of levee construction were studied, mostly by the U.S. Army Corps of Engineers (Anonymous, 1982). Particularly dangerous, but geologically unavoidable are future levee failures due to liquefaction and wave erosion in the highly seismic Delta area (Figures 8 and 17) in the event of a major earthquake.

Conclusions

Subsidence caused mostly by biochemical oxidation of peat of the reclaimed freshwater tidal marshes of the Delta locally reached 6.4 m. The

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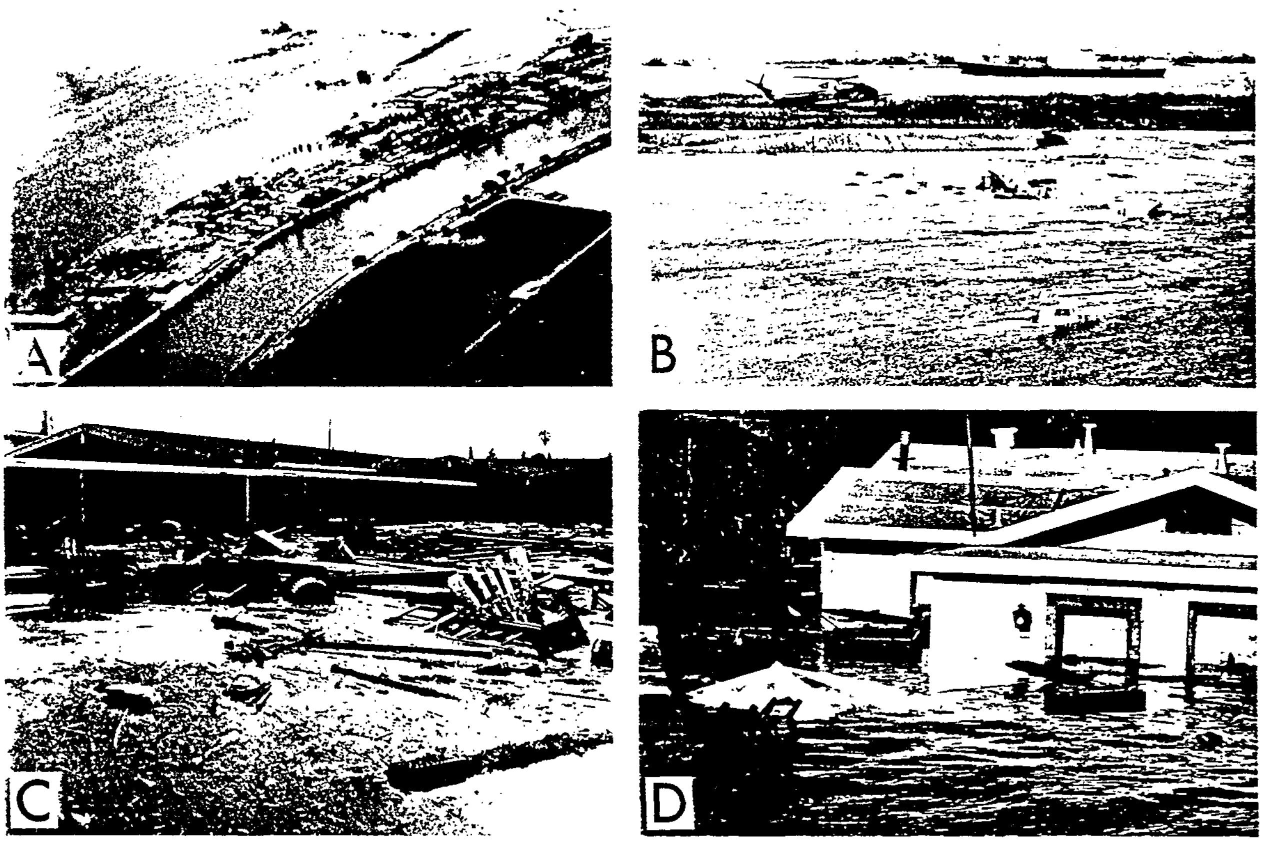

Figure 14. June 1972 flooding of Andrus-Brannan Islands. A) Aerial photo of the flooded city of Isleton on Brannan-Andrus Islands. The sewage treatment plant, far left in the photo, is partially submerged. The Sacramento River is in the foreground. B) A rescue helicopter over a flooded island and a merchant ship moving toward the city of Stockton on the Stockton Deep Water Channel. C) Isleton Elementary School on the west side of town is flooded and surrounded by floating debris. D) Floodwater on the city streets of Isleton. (All photographs by the Sacramento Bee.)

process will continue in the future and forthcoming levee failures are unavoidable. An equally unavoidable major earthquake in the area will cause liquefaction of local soils and result in a cluster of levee breaks and flooding.

Both rehabilitation of existing levees which will cost about $1 billion or the more modest grouping of several islands into a single parcel (so-called "polders"; Anonymous, 1978, 1982) will not arrest subsidence and will only prolong the deterioration of the Delta.

The loss of the Delta will hurt local agriculture and jeopardize an existing railroad as well as the vital East Bay Metropolitan Utility District aqueduct and other pipelines and power lines. Most important, however, will be the impact of the flooding on the Federal and state water developments.

It is paradoxical, but agriculture is "the number one" industry in the highly industrialized state of California. About one half of the $15 billion/year agroproduction here originates in the San Joaquin Valley. Some eight crops growing in the state (mostly in the valley) yield more than 10 percent of their world production (Figure 18).

The San Joaquin Valley has a dry climate (Kahrl, 1979) and modern agriculture here completely depends on an artificial irrigation. Such irrigation which requires voluminous water importation from northern California is achieved by two major water convenience systems—the Federal Central Valley project and the State Water Project (Anonymous, 1974, 1981a; Pafford, 1970). In both projects, surface runoff water in northern California stored in several reservoirs is delivered by gravity flow of the Sac-

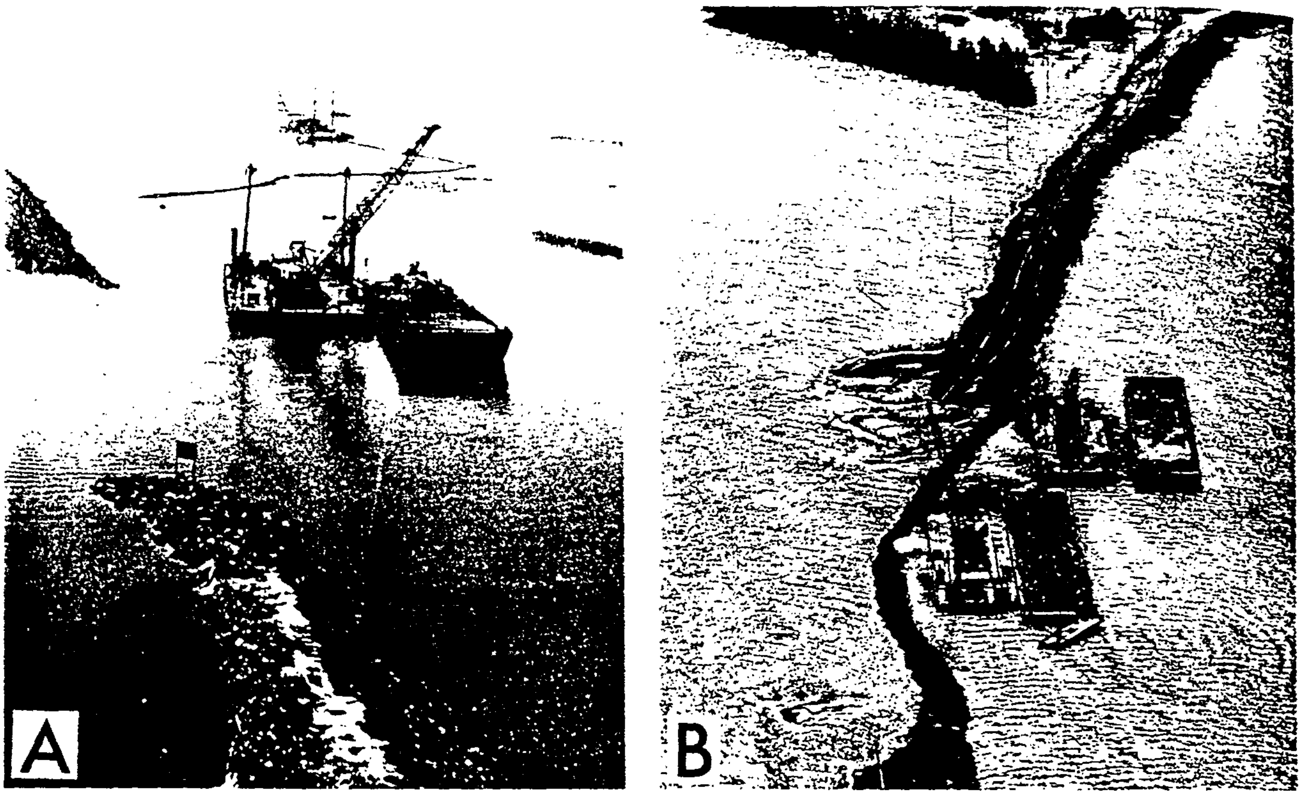

Figure 15. Repair of Delta levees. A) Rock barge and dredge work to close the 76-meter long and 11-meter deep break at Holland Tract (1980). (Photograph by the U.S. Army Crops of Engineers.) B) Closing of a major levee break on Andrus-Brannan Islands in July, 1972. (Photograph by the Sacramento Bee.)

ramento River to the Delta, from which it is pump-lifted into Federal and state canals for further deliveries to the southern part of the state (Figure 4).

The unavoidable future collapse of Delta levees and flooding of Delta islands, particularly during dry periods, will result in an intrusion of salty bay-ocean water into the Delta, and increase its salinity (for example see Figure 16). The pilot model study of the impact of flooding of Delta islands on water salinity was conducted by the U.S. Army Corps of Engineers (Anonymous, 1984) and indicated "a dramatic increase in salinity" during flooding of 19 islands at the low Delta net outflow and low export. An additional increase in salinity will be caused by evaporation from flooded islands.

It is true that the salinity tolerance of different crops varies with fruit trees and vines being less tolerant and sugar beets, cotton and barley being more tolerant to a salinity rise (Ayers and Westcot, 1976). It seems to be certain, however, that after future collapses and flooding of Delta islands, the quality of future CVP and SWP water deliveries, and consequently, the agricultural production of the San Joaquin Valley, will be jeopardized (Prokopovich, 1984). Unfortunately, the timely construction of the Peripheral Canal (Anonymous, 1968; McClurg et al., 1978) on the eastern and southern, relatively stable edges of the Delta, which will minimize the impact of such salinization was recently overwhelmingly rejected by California voters. Several other actions—such as construction of salinity barriers, etc. are now under consideration (Anonymous, 1982).

Figure 16. Salinity increase in the Delta caused by the intrusion of bay water during the June 1972 flooding of Brannan-Andrus Islands. Upper number: Chloride content (p m) prior to flooding; Lower number: Chloride content (p/m) during the post-flooding salinity peak.

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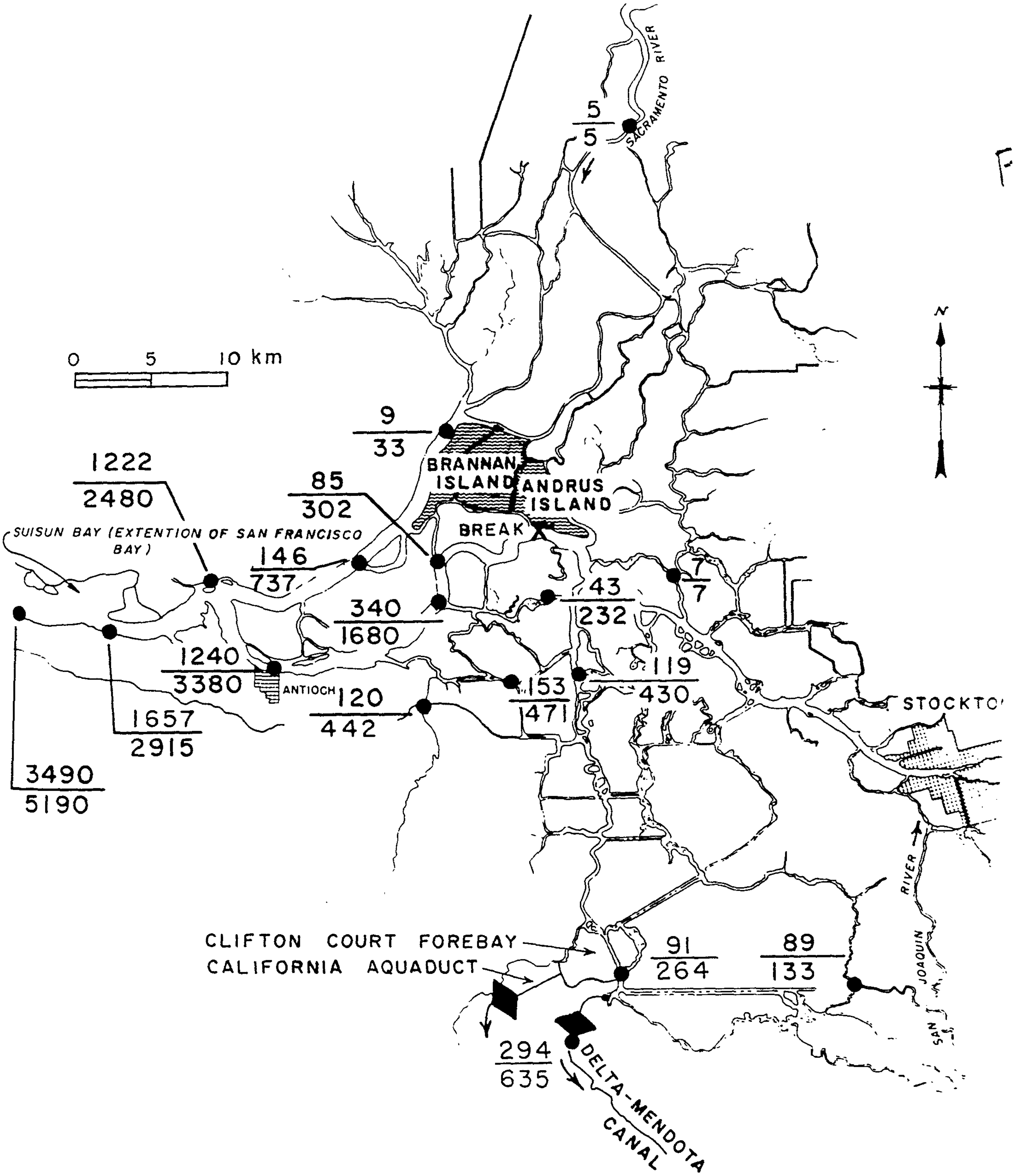

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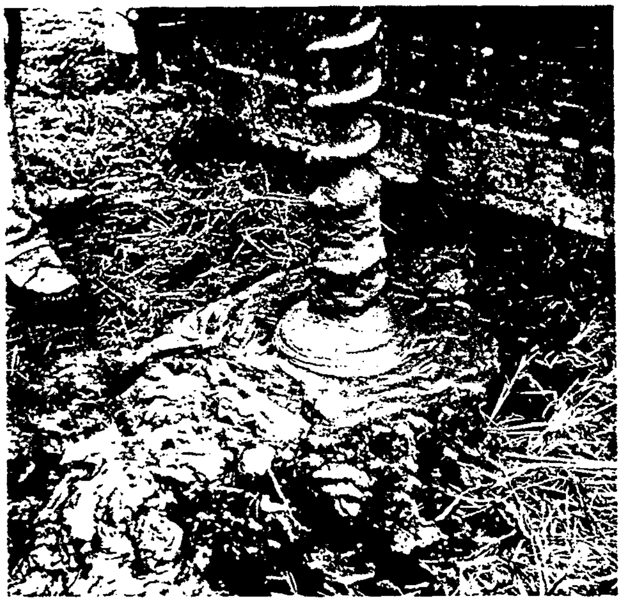

Figure 17. "Soupy" recovery (fine sand) during the 1964 flight auger drilling of AP 310 on Union Island. Such material is capable of causing liquefaction during an earthquake. (November, 1964)

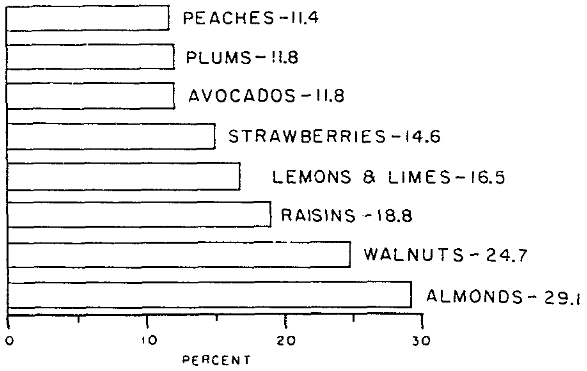

Figure 18. California's share of world production of 8 crops in 1981.

FLORIDA'S EVERGLADES

Location, Topography and Climate

Florida Everglades with some 8.094 km² of "peaty muck" is, according to Stephens (1969), the largest single peat tract in the USA (Figures 1, 19). The area is characterized by a very flat undissected terrain and is located on the southern shore of Lake Okeechobee in Palm Beach County, about 70 km east of Palm Beach (Figure 19). Local elevations are usually only about 4–6 m above sea level. The subtropical, moist climate has an average yearly temperature of about 24°C. The lowest ever recorded temperature was −4.5°C. Yearly rainfall is about 147 cm (with a recorded maximum of 213 cm). Some 60 percent of the rainfall occurs in the rainy season between June and September (Casselman, 1970).

Regional Geology

The shallow Okeechobee Lake is up to 4–6 m deep, and is the source of a large "river"—a marshy depression known as the Everglades which extends to the southern tip of the state where it enters into the ocean (Figure 19). This about 150 km long and 15–55 km wide, flat, broad, swampy trough is covered by peat of post-Wisconsin age and is underlain by limestone. Limestone also comprises the poorly-defined low ridges on the "riverbanks." The original maximum thickness of peat locally exceeded 4 m (Stephens, 1969). Deposition of Florida peat and related sediments takes place in several environmentally different areas with distinct geologic-biologic parameters which are well described in the literature (Spackman et al., 1969).

Florida peat originated primarily from sawgrass and related vegetation. Due to the high degree of decomposition, this peat has lost its original fibrous organic structure and is, therefore, usually called "muck" or "muck soil." (Young plant deposits with preserved, original fibrous structures are usually classified as peat while highly decomposed, colloidal deposits are called "muck" or "peaty muck.") Estimated average past rate of deposition of Florida peat was about 25 mm/year. Ash content of peat is usually very low, 10 to 20 percent, and organic matter content is as high as 80 to 90 percent (by dry weight); bulk density of peat is therefore rather low—about 0.2 to 0.4 g/cm³. Usually there is a sharp density decrease below the ground-water level, at the depth of 15 to 25 cm. Moisture content of peat ranges from about 100 percent at the surface to 400 percent and more at depth. The pH values of peat are slightly acidic, 5.5–6. The drainage water pH, however, is usually higher and even slightly basic with pH values ranging from 6.6 to 8. This change is caused by the influence of the underlying limestone.

Agriculture

A portion of the area with particularly thick peat covers about 310,000 hectares, or some 20 percent of the entire Everglades and has been reclaimed for agriculture by a net of drainage canals constructed since 1906. A larger, but agriculturally less suitable area with a shallow, about 0.3 to 1 m thick, peat cover was left as grassland and used as pasture. Celery, corn, beans, radishes, and leaf vegetables were the main crops. Sugarcane, introduced in the 1920's, became particularly common after the embargo of Cuban imports. At the present time the Belle Glade area is "nicknamed" as the "Sugarcane capitol of the United States" and "the winter vegetable capitol of the world." All ground-water levels in the developed area are artifically controlled and occur usually at a depth of about ½ m.

Due to the great agricultural value of the area, local peat deposits and their subsidence have been systematically studied here by a specially created, over 50 year old, Belle Glade Agricultural Research and Educational Center of the University of Florida, located some 2 miles east of the city of Belle Glade. Subsidence studies in the Center are incorporated with other agricultural research projects and include periodic leveling, installation of a "compaction recorder," microbiological investigation, studies of carbon dioxide in soils, lysimeter measurements, establishment of the relationship between subsidence rates and crop patterns and drainage patterns, etc. Various aspects of subsidence and its control in Florida are well discussed in numerous publications (for example: Stephens, 1956, 1969, 1974; Jones, 1948; Stephens and Speir, 1969; Stephens and Johnson, 1951; Shih et al., 1977a, b, c; and others).

About 80 percent of the subsidence in the area is estimated to be caused by aerobic bacterial oxidation of reclaimed swamps in the hot humid climate. Initial compaction, wind erosion, wild fires, drought spells and other factors are believed to be negligible. [Subsidence due to compaction-dehydration is, however, an important process in cooler climates where bacterial processes are less intense (Irwin, 1977; Murashko, 1969; and Prus-Chacinski, 1978, etc.)] The average rates of subsidence in the area are estimated to be about 1.5 to 3 cm/yr (Shih et al., 1977a, b). There are some indications that subsidence rates are somewhat higher in slightly elevated areas with thicker peat deposits. Such an increase in subsidence rates could be attributed to better drainage-oxidation of elevated areas and excessive compaction due to loss of bouyancy. Additional contributing factors are wind erosion and possible differences in the original composition of peat.

Periodic vertical surveys in the area since 1913 indicate that total past subsidence in the area has been on the order of 3 m (Stephens, 1956, 1969; Stephens and Speir, 1969). Consequently, the original 3–4 m thick peat blanketing over limestone is

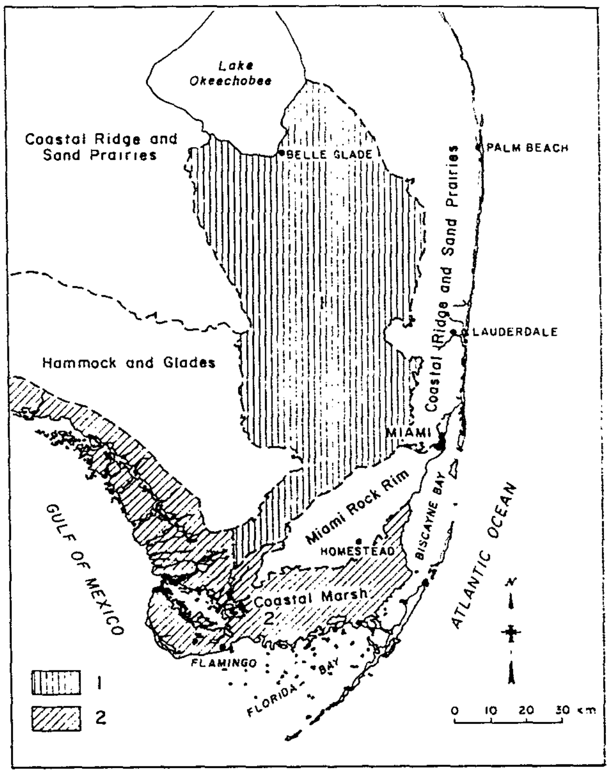

Figure 19. Distribution of peat and related deposits in southern Florida: 1) Midland peat province; 2) Coastal marsh. (Modified from Spackman and others (1969).)

reduced now to 1–2 m or less. Limestone bedrock is now visible on the bottom of some ditches and small chunks of soft limestone are common in ditch embankments, on fields, and on road levees.

Surface Evidences of Subsidence

Surface evidences of subsidence in the area are both prominent and spectacular. Some main road alignments are excavated to the bedrock and roads are built on essentially inorganic fill. Such roads are rather stable and smooth. Local roads, however, are placed on organic soil and have a "bumpy" and undulatory surface caused by differential subsidence which is additionally accelerated by compaction by traffic. These roads require periodic repairs every 3 to 4 years. A person standing near such a road experiences an "earthquake" when a heavy vehicle passes by. Since oxidation of the peat is somewhat restricted by road cover, preventing free access of air/oxygen, subsidence rates of the road beds are somewhat smaller than the subsidence rates of surrounding open ground. Roads and paved parking

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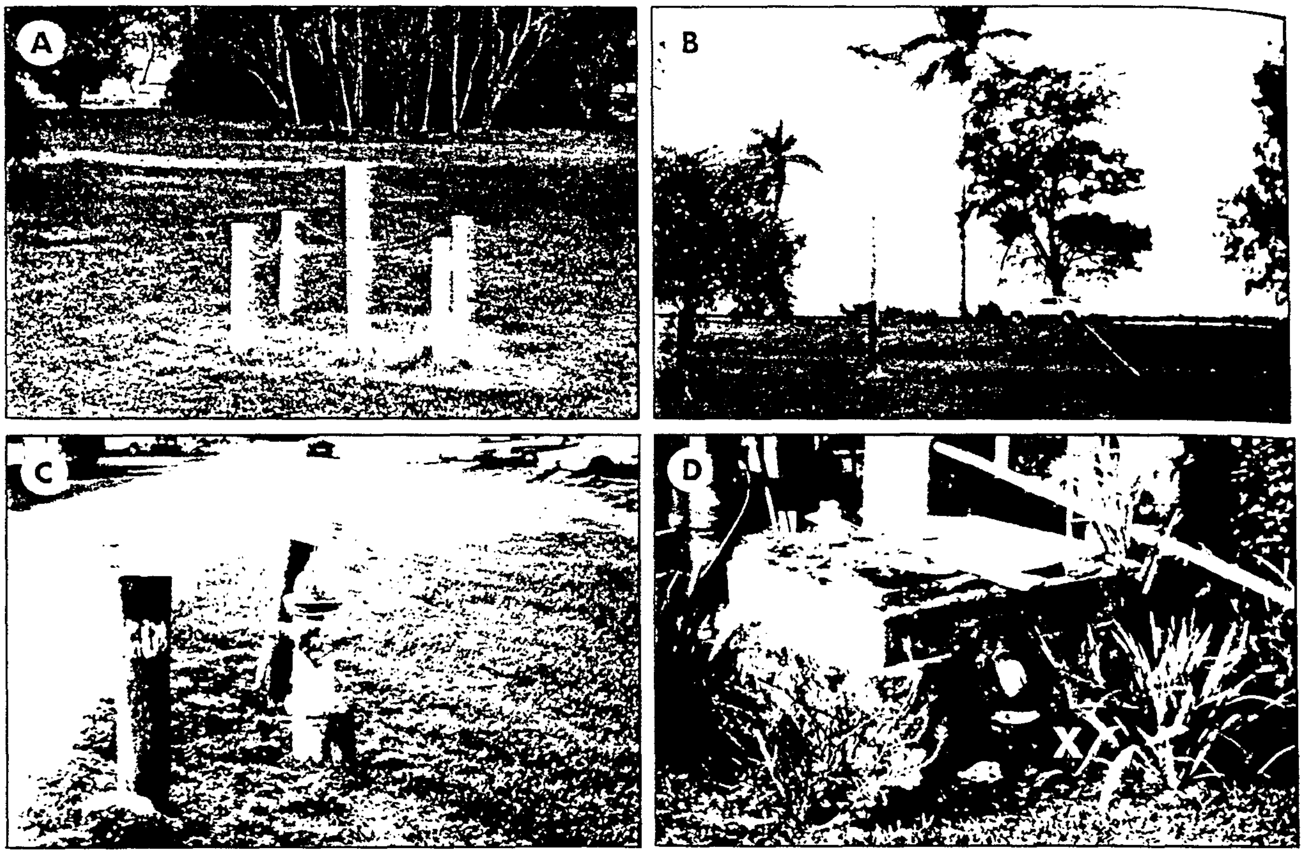

Figure 20. Selected examples of subsidence at the Belle Galde Research Center. A) Compaction reorder (a deeply seated bench mark) installed at the Center in 1912. The central concrete post with foot marks was seated on limestone bedrock at a depth of about 9 ft (2.74 m). During the installation, the top of the concrete post was at soil level. The photograph was taken in January 1978 when the recorder indicated about 1.5 m of post-installation subsidence. B) Typical blacktop road in Belle Glade area. Roadbed is notably elevated above surrounding peaty terrain due to oxidation. C) Small access road at the station is somewhat elevated above surrounding terrain. Note a riser on the fire hydrant exposed by subsidence. D) Upper part of a typical partially exposed septic tank originally buried in peaty soil. Note disrupted original plumbing.

lots are, therefore, notably elevated (0.5 to 1.5 m) above their surroundings (Figure 20B, C).

Most local houses have been built on wooden or concrete piles sunk to the limestone bedrock. Due to subsidence within their pile foundations such structures are now frequently elevated 1 to 1.5 m or more above the ground level (Figure 21A, B). The newly developed space below several houses in the Research Center is usually used as "utility rooms," "garages," storage for boats, and "dog houses," etc. Support of telephone and electric poles in the area, because of subsidence became too shallow and the poles require resetting every 3 to 4 years. Tops of many septic tanks, originally buried about 35 cm below the ground surface, are now well exposed (Figure 20D). Original plumbing of many houses requires many "unusual supports." Such modified plumbing frequently hangs in the air. Concrete floors of several workshops and garages, originally placed directly on the ground, are locally separated by up to ½ to 1 m of air space. Additional steps are added to many buildings (Figure 21C, D). Particularly impressive is a "compaction recorder" in the form of a concrete monument established in 1924, and anchored on the limestone bedrock. At the present time the upper part of the monument, originally placed at ground level, is "standing up" in the air showing amounts of peat subsidence since 1924 (Figure 20A).

Conclusions

Complete depletion of Belle Glade peat will make present type of agriculture in the area impossible. A complete arresting of subsidence here, however,

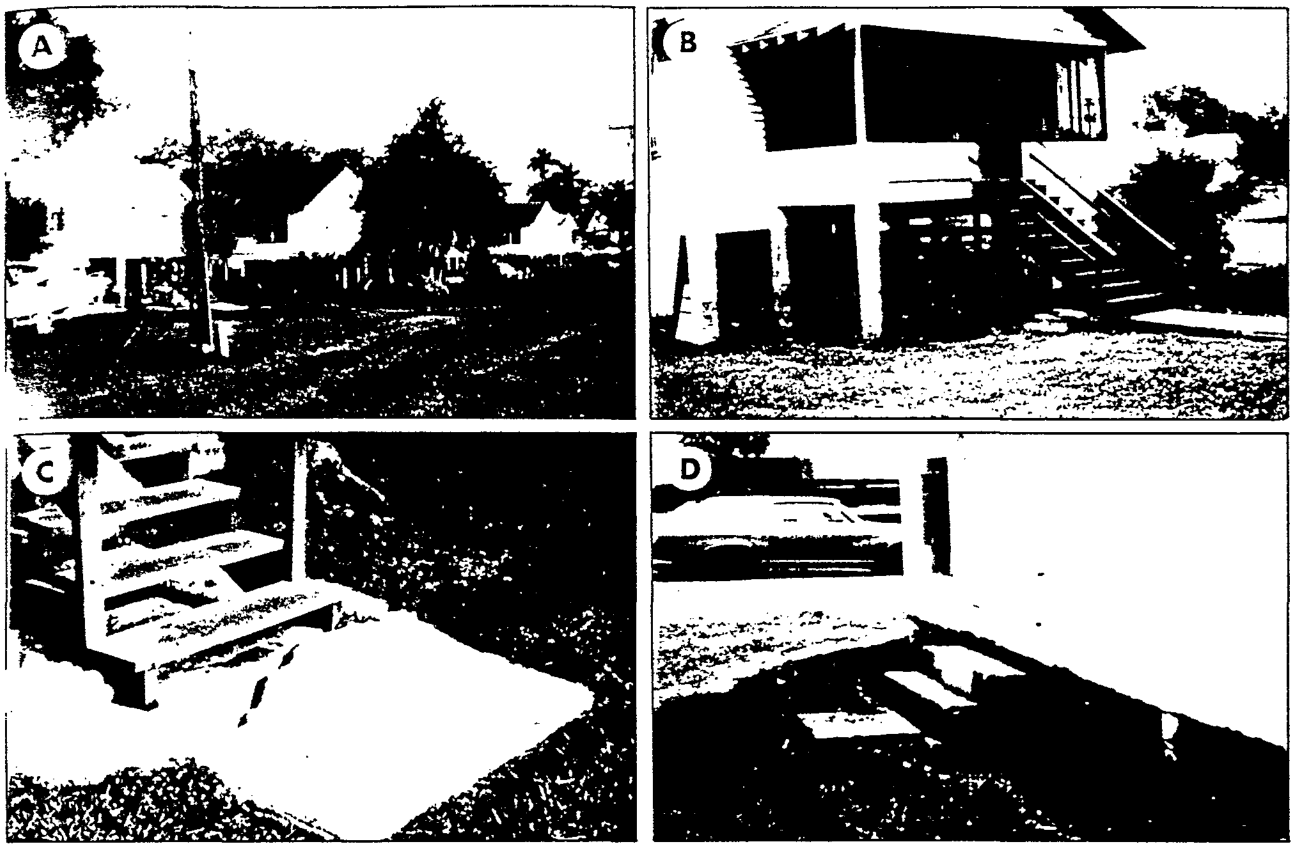

Figure 21. Impact of subsidence of peaty sediments on houses at the Belle Glade Research Center: A) General, and B) Closeup views of houses built on piles advanced through the peaty layer to the limestone bedrock. Due to oxidation of peat, the houses became elevated above ground level and steps were added at house doors. Note separation of the concrete walk at the house steps on photograph "B." C and D) Closeup view of steps progressively added at house entrances.

could be achieved only by an equally economically impossible elimination of aerobic environment, i.e., by abandoning of drainage which would result in the flooding of agriculturally important terrain. The only feasible partial control of subsidence is the decreasing of subsidence rates in the area by maintaining as high as possible the ground-water table, i.e., by strict control of agricultural use of peaty land. The available information based on field observation of subsidence, measurements of generation of carbon dioxide in soils occupied by different crops, lysimeter studies and other data indicates a certain decrease in subsidence rates with the changes of land usage in the following order: field crops, truck crops, sugarcane, virgin grass, and pasture (Shih et al., 1977a, b, c). It is hoped that data collected by the Belle Glade Research Center will be properly used by local agroindustry resulting in the partial arresting of subsidence of peat and prolonging the agricultural "useful life" of the area.

DISCUSSION

The two case histories described in this paper are a good illustration of the economic, engineering and environmental importance of subsidence of highly organic peaty deposits in a warm climate. The impact of subsidence may be either direct—such as losses of valuable agricultural land in Florida, or indirect—such as endangering giant agroindustry in California by interrupting delivery of proper quality irrigation water.

A geologist should be able to forecast potential subsidence of organic soil prior to major development of such terrains. Unfortunately, in developed countries such an early recognition is usually not applicable because development has already taken place. The possibility, however, still exists in developing countries.

Equally important is proper monitoring and recording of subsidence. Careful inspection of foundations of existing structures may provide some data as to the presence of subsidence. Installation of "deeply seated" bench marks/compaction recorders is a relatively inexpensive and probably the best method of monitoring subsidence rates in an area. Careful monitoring of ground water levels is equally important. Experience of research in Florida indicates the value of a team (geologic-agricultural) approach which resulted in the partial arresting of subsidence and in the reduction of subsidence rates. Particularly interesting and promising are recent studies of the impact of alfalfa on control of bacterial activity in peaty terrain (Levin and Shoham, 1984).

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